Determination of Oceanic Total Precipitable Water From the SSM/I

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Abstract—This paper presents results of Calibration/Validation studies of the Special Sensor Microwave/Imager (SSM/I)'s ability to measure total precipitable water in the atmosphere over the ocean. Comparisons between radiosondes and the SSM/I are presented for three different algorithms. It was found that the best fit to the data is obtained with a nonlinear global algorithm, while linear segmented and linear global algorithms give higher rms differences.

atmospheres; Marine
atmospheric condensation;

I. Introduction

THE measurement of water vapor in the atmosphere is important for disciplines such as meteorology, climatology, and hydrology. The world's oceans are the source for most atmospheric water vapor; thus, satellite measurements of water vapor over the world's oceans take on additional significance in view of the limited source of surface oceanic water vapor measurements. The evaporation of water from the oceans into the atmosphere, and its subsequent condensation into clouds and precipitation, is an important energy transport mechanism for atmospheric dynamics. The usefulness of satellite data in the study of latent heat flux has been shown by [1]. Atmospheric water parameters, when combined with other satellite and surface observations, can lead to a more complete and accurate description of meteorological events over the ocean [2].

Previous experimental instruments have shown the feasibility of making total precipitable water measurements [3]–[7]. The SSM/I, as a fully operational instrument, is an important step forward in the measurement and use of atmospheric water parameters for operational forecasting. The SSM/I is a 7-channel 4-frequency radiometer whose frequencies are 19.35, 22.235, 37.0, and 85.5 GHz. All frequencies are received in dual polarization (V and H) except 22 GHz, which is received in vertical polarization only. The SSM/I has a conical scan with a swath width of 1400 km. The SSM/I is described more fully in [8].

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The purpose of our Calibration/Validation effort was to establish how well the SSM/I and the corresponding algorithms [9] could measure the amount of total precipitable water (water vapor) in the atmosphere above the ocean's surface. If the initial values were not sufficiently accurate, then improvements in the algorithm were to be attempted.

Validating the initial algorithms required the acquisition of surface measurements from a variety of latitude zones and seasons. For the total water vapor validation, radiosonde observations (raobs) from small island stations and the few remaining weather ships were collected. Initially, a list of about 50 potential stations was compiled, with size and latitude being the only considerations. Once all the matching and screening criteria are invoked, data from only 19 stations were analyzed. The period of collection of data was from June 1987 to April 1988.

II. Surface Data Sources

The source of surface data for the validation of the SSM/I determinations of total precipitable water was the international radiosonde network. The pressure, temperature, and humidity data from the radiosondes were integrated numerically to give a value which can be compared to SSM/I values. It was required that the radiosonde station be a small island or one of the remaining weather ships. Small is defined as less than 19% of the instantaneous field-of-view (IFOV) of the 19 GHz channels. Initially, a list of 49 possible stations was prepared. Of the 49 possible stations, matches from only 19 were used. These stations are listed in Table I.

In Table I, the entries are: the name of the station, its World Meteorological Organization number, latitude with degrees south expressed as minus, longitude, the area in square kilometers, and the percentage of the 19.35 GHz IFOV that the station occupies.

The radiosondes measure pressure, temperature, and humidity at various levels in the atmosphere. These measurements are then transmitted worldwide to various meteorological centers, including NMC. The raobs and selected surface observations are combined with matching SSM/I brightness temperatures to form a data set which can be used to evaluate algorithms for deriving total precipitable water over the ocean.

The radiosonde message contains the three parameters required to calculate the total precipitable water. These

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TABLE I
RADIOSONDE STATIONS

Name	Number	Latitude	Longitude	Area	% IFOV
Macquarie Is.	94998	−54.50	158.95°E	109	4.41
I. N. Amsterdam	61996	−37.80	77.53°E	62	2.51
Easter Is.	85469	−27.17	109.43°W	117	4.74
Cocos Is.	96996	−12.18	96.83°E	14	.57
Diego Garcia	61967	−7.35	72.48°E	152	6.15
Isla San Andreas	80001	12.58	81.70°W	20.5	.83
Barbados	78954	13.07	59.50°W	431	17.45
San Maarten	78866	18.05	63.12°W	85	3.44
Roberts Fld.	78384	19.30	81.37°W	183	7.41
Ishigakijima	47918	24.33	124.17°E	215	8.70
Minamidaito Jima	47945	25.83	131.23°E	46.6	1.89
Kindley Field	78016	32.37	64.68°W	53	2.15
Hachija Jima	47678	33.12	139.78°E	69.9	2.83
Coca	C7C	52.75	35.50°W	OK	OK
Lima	C7L	57	20.00°W	OK	OK
St. Paul Is.	70308	57.15	170.22°W	90.6	3.67
Mike	C7M	66	2.00°E	OK	OK
Jan Mayen	01001	70.93	8.67°W	373	15.10
Bjornoya	01028	74.52	19.02°E	179	7.25

parameters are: the pressure, air temperature, and dew point depression (DPD). The DPD is the difference between the air temperature and the dew point temperature in °C. Utilizing Teten's formula [10], the vapor pressure of water vapor can be calculated. Next, the mixing ratio of water to dry air is calculated. The total precipitable water is calculated from the equation

$$U = 1/g \int q \, dp.$$

This integral is evaluated using the trapezoidal rule, or $U = 1/2g \, \Sigma(q_i + q_{i+1})(p_i - p_{i+1})$, where g = acceleration of gravity, q_i = the mixing ratio of water vapor to dry air at the ith level, and p_i = pressure at the ith level.

III. Data Handling

Daily radiosonde reports from the selected stations were collected from NMC computer files. The corresponding report of surface observations from that station was also collected from NMC.

Matches between the SSM/I and the raobs were made with the matching criteria being the surface and satellite observations must be coincident within 2° of latitude and longitude and 2 h. Most radiosondes are launched at 0 and 12 UTC, while the SSM/I has approximately 0600 LST ascending node. This serves to eliminate many stations.

The screening criteria are based on the quality and completeness of the raobs, eliminating overlapping orbit matchups, and the presence of sea ice or precipitation. The raobs are screened for missing surface pressure, supersaturation, and superdiabatic lapse rates. Those with missing surface pressures were corrected if possible. The others were eliminated from the statistics. If the radiosonde did not reach 300 hPa, a correction proportional to the pressure and the amount of water vapor in the sounding was made. If the raob reaches 300 hPa or higher, then no correction was made. Only the single pixel closest to the radiosonde station was used in our analysis.

When working with data sets like the ones used in this investigation, there are many potential sources of errors in both the satellite data and the raobs. Even though several screening checks were applied, a scatter plot, (like Figs. 3–5) of the entire data set convinced the authors that there were several suspect points or outliers in the data set. Following procedures outlined in [11], a 2% trim was applied to the data to remove these outliers.

Details and documentation of the software developed for the data handling in this investigation are given in [12].

IV. The Initial Algorithm

The algorithms that were in place when the SSM/I was launched are divided into latitudinal and seasonal zones, called climate codes. These algorithms were developed by the Hughes Aircraft Corp. There are 11 climate codes per hemisphere. Each parameter is retrieved with a linear four-channel algorithm. For the water vapor retrievals, there were three distinct sets of coefficients that were used in each hemisphere. The structure of the initial or Hughes algorithms is given in greater detail in [9].

In addition to validating the algorithms for each climate code, it was felt that it was necessary to check for the existence of gradients at the boundaries of the climate codes. Fig. 1 shows the boundary discontinuities between climate codes. This figure shows data for August 11, 1987 for revs 740, 741, and 742. The land masses shown are Africa and Saudi Arabia on the left and Madagascar in the center swath. Red denotes flagged areas which are either land or areas of precipitation. Revs 740 and 741 clearly show the boundary at the equator. A less sharp boundary also appears near 25 South in Rev 740. A sharp air mass boundary is shown at about 20 South. Lesser amounts of water vapor are shown in blue, and increasing amounts are shown in warmer tones (i.e., yellow and red).

Table II shows the latitudinal zones that comprise the Hughes algorithm. The zones that are only 5° of latitude wide are transition zones, but the boundaries of all the zones are hard. Table II shows the comparisons for the Hughes algorithm with radiosonde determinations for the latitude zones and also globally. All entries in the table are kg/m^2 or precipitable millimeters. The columns labeled "Mean" show the mean value for all the retrievals and radiosondes for that particular latitude zone. The columns labeled "Std Dev" (standard deviation) are the natural variance of the sample set. This is the variance exhibited by the total precipitable water in this climate zone. The column labeled "Rms Diff" is the rms difference between the SSM/I retrieval and the corresponding radiosonde value. The column labeled Bias is the difference between the mean SSM/I retrieval and the radiosonde retrieval. A negative bias indicates an underestimate by the SSM/I, and a positive bias indicates an overestimate.

The results presented in this table are a composite of results obtained from the three sets of coefficients used to retrieve water vapor. The algorithm used in the polar re-

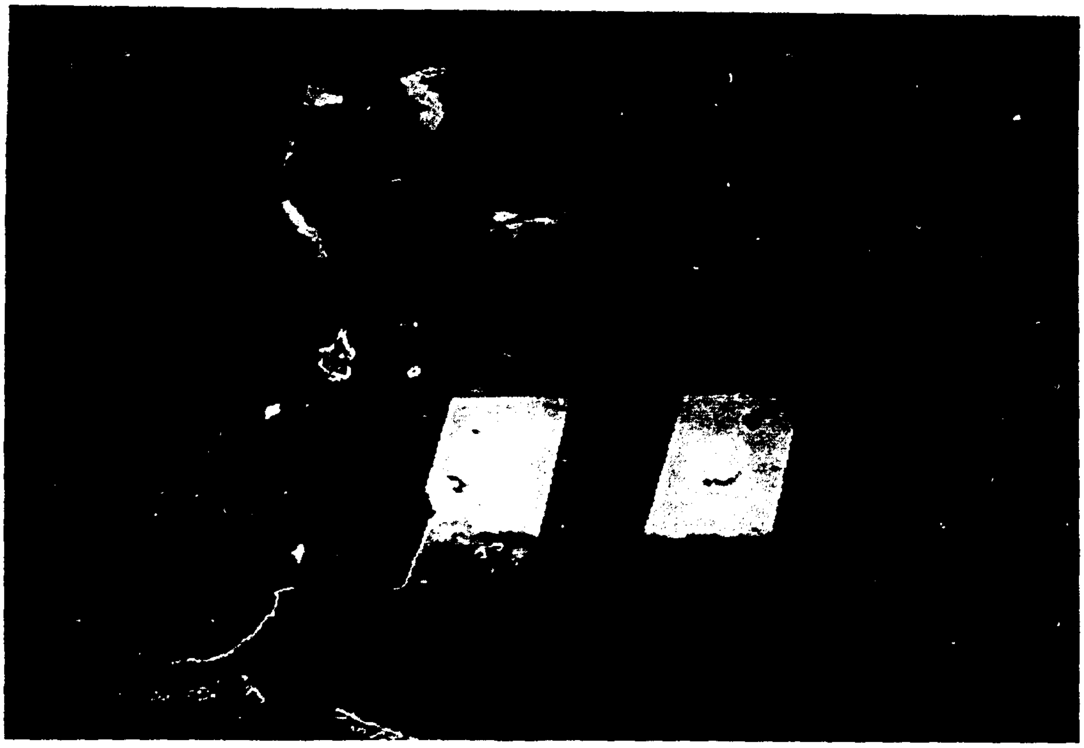

Fig. 1. Revs 740-2 showing gradients at the geographic boundaries of the climate codes of the Hughes algorithm. The area shown is the Indian Ocean. Gradients are notable at the equator and at 25° latitude. Lesser amounts of water vapor are shown in blue, and increasing amounts are shown in yellow and red. Solid red areas are flagged values and indicate land or precipitation.

Fig. 2. Revs 740-2 (same as Fig. 1) with retrievals using the NESDIS algorithm. The global algorithm does not produce artificial gradients.

gions has a distinct tendency to underestimate the amount of water vapor that is present, and the algorithm used in the warn tropics shows a tendency to overestimate the amount of water vapor that is present. These two tendencies effectively cancel each other out as the global data set shows a negligible bias. All of the rms differences are

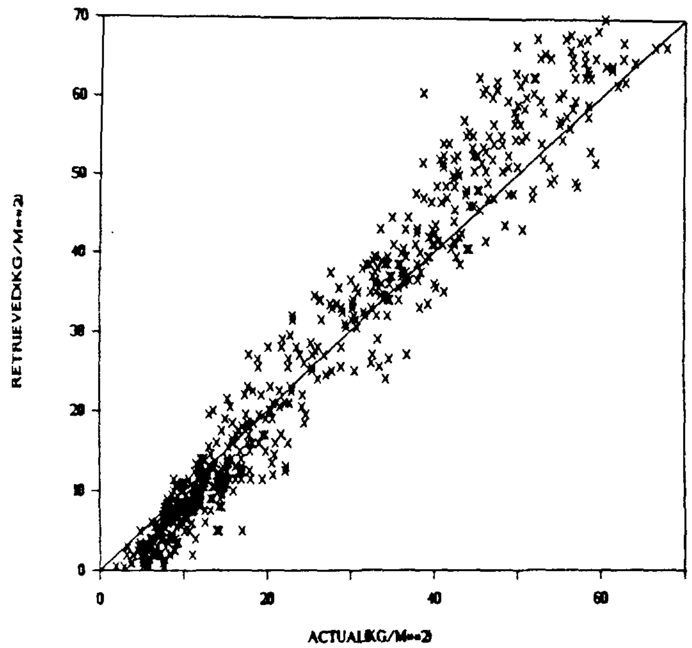

Fig. 3. Retrievals from the Hughes algorithms versus raobs. Units are in kg/m^2 or precipitable millimeters. Values are from the trimmed data set and are composited from the three sets of coefficients that comprise the Hughes algorithm for total precipitable water.

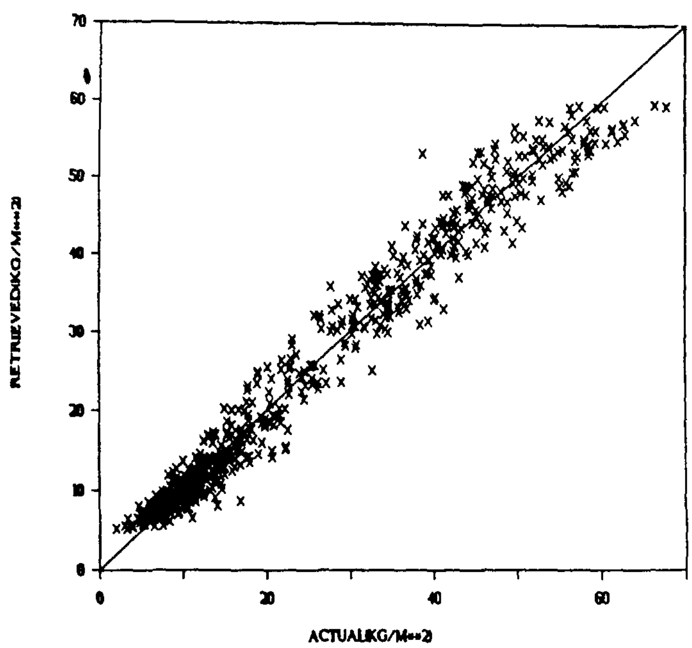

Fig. 4. Retrievals from the NESDIS or improved algorithm versus raobs. Units are in kg/m^2 or precipitable millimeters. Values are from the trimmed data set and were derived with a global nonlinear algorithm.

TABLE II
LATITUDINAL ZONES COMPRISING THE HUGHES ALGORITHM

Latitude Zone	Sample Size	Mean Ret	Mean Raob	Std Dev Ret	Std Dev Raob	Rms Diff	Bias
60°-90°N	209	8.7	11.0	4.3	4.2	3.2	−2.3
55°-60°N	37	12.7	13.3	10.6	8.0	3.8	−0.6
25°-55°N	59	23.6	27.1	15.0	14.0	5.2	−3.5
20°-25°N	35	45.3	38.9	13.8	12.2	7.4	6.3
0°-20°N	134	44.2	39.8	11.7	9.0	6.7	4.4
0°-20°S	66	53.8	50.4	10.2	9.3	6.3	3.4
20°-25°S	0						
25°-55°S	47	23.5	22.2	11.1	9.9	3.8	1.3
55°-60°S	0						
60°-90°S	0						
Global	587	27.0	26.3	20.1	16.9	5.1	0.7

larger than the desired 2 kg/m^2. Fig. 3 is a scatter plot of the global data set.

At least two factors are sources of difference between the radiosonde and the SSM/I derived values of total precipitable water. One is the errors in the radiosonde determinations of temperature, pressure, and humidity. A coefficient of variance of 0.042 for U.S. radiosondes was obtained in [6]. This translates into an error of 1.1 kg/m^2 for this sample set. Another factor is the small scale variability in water vapor. An estimate of this was obtained by comparing values derived from the SSM/I with each other. The rms difference between the sample closest to the raob matchup and the other three matchups is 1.5 kg/m^2. When these two factors are taken into account, the rms difference between raobs and the Hughes algorithm becomes 4.7 kg/m^2. The data presented in Table II and shown in Fig. 3 are from the trimmed data set.

V. Improved Algorithm

Three basic considerations led to the form of the improved or NESDIS algorithm. The first was the desire to eliminate the discontinuities at the boundaries of the Hughes segmented algorithm. The second was to construct a linear algorithm. The third was to be as accurate as possible. An initial constraint was that the algorithm could only use four channels. The approach that was followed was to regress the corresponding brightness temperatures against the total water vapor as determined from the raobs for coefficients using the entire data set to produce one global algorithm. As part of the analysis, all possible combinations of the SSM/I channels (excluding the 85 GHz V channel) were investigated. This procedure would provide the optimum retrievals and also be useful in the event of channel failure. Previous experience with the SMMR instruments on Seasat and Nimbus 7 shows that it is possible to achieve rms differences between satellite and radiosonde in the mid-2 kg/m^2 range [6], [7]. Both the SMMR algorithms are global algorithms.

Efforts to construct a linear algorithm with the desired accuracy were unsuccessful. Rather than reintroduce the boundary discontinuity problem by using a series of linear algorithms, a nonlinear, but global, algorithm was constructed. We introduced the square of the brightness temperature of the 22.235 GHz channel as a predictor, and used standard regression techniques to find the best four-

TABLE III
RESULTS FROM THE NONLINEAR ALGORITHM

Latitude Zone	Sample Size	Mean Ret	Mean Raob	Std Dev Ret	Std Dev Raob	Rms Diff	Bias
60°-90°N	209	11.0	11.0	3.8	4.2	2.0	0.0
55°-60°N	37	14.1	13.3	7.7	8.0	1.9	0.8
25°-55°N	59	26.2	27.1	14.4	14.0	3.3	−0.9
20°-25°N	35	41.3	38.9	11.1	12.2	3.7	2.4
0°-20°N	134	40.3	39.8	9.2	9.0	3.5	0.5
0°-20°S	66	48.2	50.3	8.2	9.3	4.3	−2.1
20°-25°S	0						
25°-55°S	47	22.8	22.2	10.2	9.9	2.6	0.6
55°-60°S	0						
60°-90°S	0						
Global	587	26.3	26.3	16.7	16.9	3.0	0.0

channel fit. In addition to the squared term, the other predictors are 19, 22, and 37 V. The equation is: $WV = a_0 + a_1 T_B^{19V} + a_2 T_B^{22V} + a_3 T_B^{37V} + a_4 (T_B^{22V})^2$, where $a_0 = 232.89393$, $a_1 = -0.148596$, $a_2 = -1.829125$, $a_3 = -0.36954$, and $a_4 = -0.006193$. The selection of the square of the water vapor channel brightness temperature as the nonlinear variable was largely a matter of what would cause the least change in existing software. Other nonlinear algorithms have been described in [13] and [14].

The results from the above algorithm are summarized in Table III. As before, all table entries are in kg/m^2.

When the radiosonde variance and small scale fluctuations in the water vapor distribution are taken into account, the rms difference decreases to 2.4 kg/m^2. Fig. 4 is a scatter plot of the retrieved versus raob values of total precipitable water from the nonlinear global algorithm. The lack of bias and reduced rms difference is indicated by the way the points cluster about the "perfect fit" line. Fig. 2 shows the same revs as in Fig. 1, but presents water vapor retrievals using the global algorithm. The sharp gradient at the equator seen in Fig. 1 is not present in Fig. 2. The color scale is the same as in Fig. 1.

VI. DISCUSSION

The results presented here show the possibility of a distinct improvement in the retrieval of total precipitable water over the ocean. The global, nonlinear algorithm will be more sensitive to cloud liquid water content, rain, and sea ice. The additional sensitivity is due to the screening of rain and sea ice from the dependent data and the squared term in the retrieval algorithm. Thus, it will be very important to have good screening procedures for identifying these conditions.

When attempting to derive a linear algorithm, a distinct nonlinearity between retrieval and raobs was noted. This is shown in Fig. 5 which shows raob versus retrieval for a linear four-channel algorithm. The linear algorithm overestimates in the mid-range and underestimates at large values of total precipitable water. This effect had been

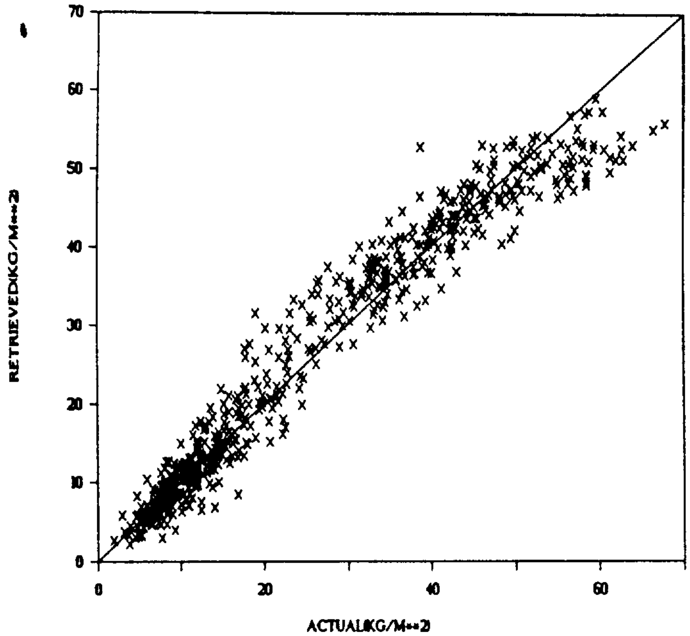

Fig. 5. Retrievals from a linear global algorithm developed at NESDIS versus raobs. Units are in kg/m^2 or precipitable millimeters. The linear algorithm has significant nonlinearities in the retrievals. It shows a tendency to overestimate at medium values and to underestimate at large values.

noted previously [5] with data from the Scanning Microwave Spectrometer (SCAMS) flown on Nimbus 6. The explanation for this effect is probably related to the selection of the center of the water vapor line as the operating frequency of the SSM/I water vapor channel. The line center is most likely to exhibit a saturation effect at large water vapor amounts, and pressure and temperature effects can also be important, depending on the distribution of water vapor in the atmosphere.

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